Seismic Response Analysis of Piece-Wise-Linear Hysteretic Strucures Based on Stochastic Linearization(等価線形化法に基づく区分線形履歴構造物の不規則地震応答解析)

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論　文　内　容　要　旨

CHAPTER ONE : INTRODUCTION

We can state that in most of the practical situations, structures during their lives are exposed to dynamic loading. This loading can result from several different sources including earthquake ground motion, high winds, severe sea waves, tsunamis, moving vehicles, rotating and reciprocating machines, and others. Undoubtedly, among the loads the earthquake is of great significance to the structural engineers in one way or another. However, the basic mechanisms within the earth which give rise to the earthquake are not yet fully understood. As a consequence, it is impossible to describe in a deterministic way the earthquake ground motion exactly in a particular site at a given time in the future. From the standpoint of engineering, this characteristic of the earthquake is referred to the randomness belonging to the earthquake itself. Due to this randomness, a particular earthquake history recorded in the past may bear little significance to structural design when it is applied as the ground motion to a structure to be built. This comment suggests that the input motion induced by the earthquake should instead be treated as a probabilistic or stochastic process.

On the other hand, almost any type of the structures subjected to dynamic loading may behave nonlinearly and inelastically, and especially exhibit hysteretic characteristics under severe loading. The term "hysteretic characteristics" in structural dynamics means that the dynamic behaviour depends not only on the instantaneous state but also on its past history. The exact nature of the hysteretic component is dependent on structural materials, geometrical configuration and environmental conditions as well as the dynamic loading, and may vary greatly from structure to structure. In order to suit the convenience of design procedure and analytical treatment, this characteristic of many types of the practical structures are idealized through expressing them into a large body of tractable models, including the bilinear model, double—bilinear model, trilinear model, poly—linear model, slip model, peak—oriented model, origin—oriented model, Clough's model, Takeda's model, Kato—Akiyama's model, Wen's model, etc. It is of great interest to notice that these models except the Wen's model show a common property that the hysteretic characteristics consists of piece—wise—linear behaviour. As a consequence, we name such models in this paper the piece—wise—linear hysteretic models or PWL hysteretic models for short.

For reasons of assessing the safety and evaluating the dynamic performance of the structures, it is necessary to do the stochastic response analysis for the structures under random seismic excitations, taking the nonlinear hysteretic behavior into account. This significance of the seismic response analysis can be understood in another way. That is, it leads to a good insight into the structural behaviour under the imposed earthquake ground motions.

The purpose of this paper is to develop an approach to stochastic response analysis of PWL hysteretic structures under physical seismic noise excitations, based on an improved version of the stochastic linearization method.

CHAPTER TWO : GENERAL REVIEW OF STOCHASTIC RESPONSE ANALYSIS

In this chapter, various methods for stochastic response analysis of nonlinear systems have been summarized briefly. From the general review we can state that extensive exploration and vast efforts have been made during the last period of years, aiming at developing the highest—potential method to stochastic response analysis of nonlinear systems. In spite of the fact that the methods described above often reveal their own advantages or superiorities over others in a certain aspect, a number of severe limitations or drawbacks are still involved, including

1) *the restriction conditions imposed on the forms of nonlinearity and/or excitation noise,*

2) the poor accuracy or reliability of the resuls obtained for strongly nonlinear or yielding

systems,

3) the lack of applicability to practical structures,

4) the complexity in analytical treatment,

5) the high cost and heavy calculation, etc.

In order to be useful for practical application, the method to stochastic response analysis has to be able to cope with those problems.

CHAPTER THREE : STOCHASTIC LINEARIZATION TECHNIQUE BASED ON WEIGHTED LEAST−SQUARE MINIMIZATION

In this chapter, an improved version of the stochastic linearization method has been developed in details, based on the weighted least−square minimization criterion. In this version, the non−Gaussian properties or non−normality of the response in the nonlinear system has been taken into account in the sense that the weighting functions reveal the difference of the distributions of the response between the nonlinear and equivalent linear systems. The closed forms of the equivalent linear coefficients can be gained simply through applying partial differentiation and expectation operation directly to the nonlinear terms involved in the nonlinear system. This version is quite tractable analytically and no more efforts are needed in order to employ it than to apply the Atalik and Utku's technique. This statement can be, in fact, easily proven through comparing the following expressions.

The present version of stochastic linearization leads to

for a hardening system

$$a_{ij}=E\left[\left. \frac{\partial g_i}{\partial x_j} \right|_{X=2/\sqrt{5}X} \right] \tag{3.16}$$

and for a softening system

$$a_{ij}=E\left[\left. \frac{\partial g_i}{\partial x_j} \right|_{X=4/\sqrt{15}X} \right] \tag{3.17}$$

while the Atalik and Utku's linearization technique describes

$$a_{ij}=E\left[\frac{\partial g_i}{\partial x_j} \right] \tag{3.18}$$

regardless of either softening or hardening systems.

Sequentially, in order to investigate its accuracy, the present stochastic linearization version has been applied to a certain number of nonlinear systems, hardening or softening, with one−dimensional or two dimensional nonlinearities. It has been shown that the present version produces better approximate solutions and its accuracy is raised about 10% over the Atalik and Utku's technique. In a word, this version of stochastic linearization is more dependable to assess the response of a heavily nonlinear or strongly yielding system.

CHAPTER FOUR : STOCHASTIC PESPONSE ANALYSIS OF THE PWL HYSTERETIC STRUCTURES UNDER GW OR FGW SEISMIC EXCITATIONS

This chapter has dealt with the stochastic response analysis of the PWL hysteretic structural systems subjected to GW or FGW random noise excitations. First, we have proposed in Section 4.2 the general formulation for the PWL hysteretic models which describes

$$\Phi = \alpha x + (1-\alpha) z \tag{4.1}$$

$$\dot{z} = \frac{A}{D_y}[1 - U(\dot{x})U(z-1) - U(-\dot{x})U(-z-1)] \tag{4.8}$$

In order to apply the stochastic linearization technique developed in Chapter Three to the problem, a simple approach to smooth the PWL hysteretic models in a probabilistically equivalent way has presented in Section 4.3. As a result, the following smooth differential expression has been developed

$$\dot{z} = \lambda[\kappa \dot{x} - \beta |z|^n \dot{x} - \gamma |\dot{x}| z |z|^{n-1}] \qquad \text{for a positive } n \tag{4.12}$$

which is to describe the smooth−varying hysteretic characteristics corresponding to the PWL hysteretic models.

Furthermore, to cover a larger class of nonlinear hysteretic characteristics, expression(4.12) has been extended in Section 4.4 into

$$\dot{z} = \lambda[\dot{x} - 0.5 |z|^n \dot{x} - 0.5 |\dot{x}| z |z|^{n-1}] \qquad \text{for a positive } n \tag{4.17a}$$

which is referred to as the extended hysteretic structural models. Expression (4.17a) can represent a very large body of nonlinear systems, being softening or hardening as well as deteriorating. More importantly they can express the well−known PWL hysteretic models by properly choosing the values of parameters κ, γ, β and n.

The stochastic response of the extended hysteretic structural systems, including not only covariance matrix but also maximun displacement, has been evaluated. First, on the basis of the improved version of stochastic linearization presented in the foregoing chapter, the differential equations related to the covariance matrix response has been derived in Section 4.5. Sequentially, an approximate, yet efficient explicit integral expression for the moment functions of the maximim displacement response has been deduced in Section 4.6. Further, in order to investigate the accuracy of the present approach, some numerical examples have been illustrated in Section 4.7. Through making a comparison between the analytical results and the Monte−Carlo simulations for the bilinear model, the accuracy has been verified satisfactorily.

In addition, we have generated the foregoing approach to the stochastic response analysis of the extended hysteretic models under bi−directional random excitations in Section 4.8. At first the models for the bi−directional restoring forces have been developed, following the uniaxial extended hysteretic models. Then, the previous stochastic linearization technique has been applied to the stochastic response analysis of the problem. Finally, in Section 4.9 the application of the foregoing approach to MDOF hysteretic systems has been illustrated and the comparison of the results by the analytical approach and Monte−Carlo simulation has been also shown.

CHAPTER FIVE : STOCHASTIC RESPONSE ANALYSIS OF THE PWL HYSTERETIC STRUCTURES UNDER NG AND/OR NW SEISMIC EXCITATIONS

In this chapter, we have presented an approach to the stochastic response analysis of the PWL hysteretic systems subjected to NG and/or NW random noise excitations. The stochastic response has been characterized by the cumulant functions instead of the conventional moment functions. This approach has provided a way to study the effect of both the non−normality and the non−whiteness of the excitation noises upon the stochastic response.

In Section 5.2, the excitation noises have been categorized in terms of normality and whiteness and then in order to apply the Markov theory, a technique to replace a NW excitation noise by a white process has been described as well. In Section 5.3, we have derived the differential equations for cumulant response through introducing the multi−dimensional stochastic equation and furthermore have presented the cumulant evaluation of the products of the response and excitation.

In addition, the following results have been deduced in conclusion.

1) From the differential equations for cumulant response(5.17) and (5.18) we can see clearly that the non−normality of the excitation exerts no influence upon the 2 nd cumulant response.

2) Some numerical illustrations to the special case of the PWL hysteretic systems, which correspond to $\alpha=1.0$, i.e, the linear system,show that the 4 th cumulant responses $k_4(x^3\dot{x})$ and $k_4(\dot{x}^3x)$ can be considered to be negligible, when compared to $k_4(x^4)$ and $k_4(\dot{x}^4)$.

In Section 5.4, the present approach has been applied to both NW random noise and NG random noise excitations, Through making a comparison with other studies, the efficiency and reliability of the present approach has been investigated. As a result, it has been shown that if the excitation has small correlation time τ_{cor} the replacement technique presented here yields very satisfactory results.

CHAPTER SIX : APPLICATION TO CONTROLLED STRUCTURES

An attempt to circumvent the problems related to the sole application of either passive or active control,through combining passive and active control, which is embodied in form of a base−isolated structure with active tendon control, has been made in the present Chapter. Through conducting the deterministic response analysis of the structure excited by the NS component of the 1940 El Centro earthquake, the feasibility and efficiency of combining passive and active control of structures have been verified satisfactorily. Finally, on the basis of the stochastic response analysis of the PWL hysteretic structures developed in the previous chapters, the response assessment of the proposed structural model with both active and passive control under random excitation noises has been performed.

CHAPTER SEVEN : CONCLUSIONS

This chapter is to conclude this paper by summarizing the obtained results and further indicating the research topics for future study.

審 査 結 果 の 要 旨

建築構造物の耐震設計に当たっては，将来発生する不規則性の強い非定常的な地震動による建築構造物の非線形応答を確率過程として推定する必要がありながら，実用可能な手法は未だ開発されていなかった。

本研究は，様々な非線形履歴特性を有する構造物がNon－Gaussian性およびNon－White性を有する非定常な地震入力を受ける際の不規則応答解析の一般式を展開して，確率過程に基づく耐震設計手法を確立したもので，本論文は全7章より構成されている。

第1章は序論であり，本研究の目的及び意義について記している。

第2章は非線形不規則応答解析に関する既往の研究を整理し，問題点を抽出した上で，本研究の意義を明らかにし，本論文の位置付けを行なったものである。

第3章では，強い非線形性を有する構造物の挙動推定において，その応答が正規分布から偏ることを考慮して，等価線形係数を重み付き最小2乗法の規範を用いて導出する等価線形化法を提案・定式化し，またこの手法を用いた場合，十分な精度が得られることを確認している。

第4章では多くの実履歴系構造物を表現できる区分線形履歴構造物モデルの統一的かつ一般的な表現式を提案した上で，3章で展開した手法を用いてGaussian WhiteまたはFiltered Gaussian White入力を受ける一般的な履歴構造物の不規則応答解析法を確立している。

第5章では，Non－Gaussian Non－White入力を取り扱えるように，前章のアプローチを，その不規則応答解析を多次元Stochastic Equationを導入したキュムラント関数で評価する方法にまで拡張している。

第6章では，本解析理論を制振建築構造物に応用し，手法の適応性を示している。

第7章は結論である。

以上要するに本論文は，履歴特性を有する構造物の非定常不規則地震動に対する応答解析用確率過程理論を，種々の履歴特性を統一的に取扱い得る一般式で表現し，重み付き等価線形化法を用い展開して，実用可能な手法を確立したものであり，建築工学特に耐震工学の発展に寄与するところが少なくない。

よって，本論文は工学博士の学位論文として合格と認める。